Stormwater Management in a Time of Climate Change: Insights from a Series of Scenario-Building Dialogues

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ABSTRACT

Numerous decision support tools have been developed to assist stormwater managers to understand future scenarios and devise management strategies. This paper presents one such tool, the Vulnerability, Consequences, and Adaptation Planning Scenarios (VCAPS) process, and reports on experiences from its deployment in 10 coastal communities on the Atlantic and Gulf coasts. VCAPS helps to elucidate local complexities, couplings, and contextual nuance through dialogue among technical experts and those with detailed contextual knowledge of a community. Participants in the process develop qualitative scenarios of climate change impacts and how different management strategies may prevent or mitigate undesirable consequences. The scenarios help stormwater managers diagnose potential problems that may emerge from climate change and variability, which can then be subject to further detailed analysis. The authors describe five challenges faced by stormwater managers and how insights that emerge from scenario-based processes like VCAPS can help address them: characterizing the implications of interacting climate stressors that originate stormwater, bringing all available expertise and local knowledge to bear on the problem of stormwater management, integrating local and scientific information about coupled human–environment systems, identifying management actions and their trade-offs, and facilitating planning for sustained coordination among multiple public and private entities.

1. Introduction

Stormwater management is an increasingly difficult challenge for coastal and inland communities. Aging and overloaded infrastructure, expanding areas of impervious surfaces, increasing alteration of landscapes, shifting connections between human and natural systems, and increasing standards for ecological compliance exemplify the characteristics of human and social systems that contribute to challenges of stormwater management (National Research Council 2009; Debo and Reese 1995; Postel and Richter 2003; Poff et al. 2007). Climate change and variability are likely to exacerbate the challenges and impacts; existing problems may become worse and new problems may emerge (Mellilo et al. 2014; Burkett and Davidson 2012; Arisz and Burrell 2006; Hirschman et al. 2011; Rosenberg et al. 2010).

Impacts from stormwater—the runoff from rainfall and snowmelt that does not percolate into the ground but instead flows freely over land and impervious surfaces—can affect human and natural systems including social and health services, emergency services, business, recreation, utilities, transportation systems, local environmental resources, government services, and municipal budgets. For example, stormwater can inundate and erode roadways,

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flood underground spaces and facilities, flood homes and businesses, transport debris and sand into culverts blocking drainage systems, disable wastewater treatment facilities, and mobilize hazardous chemicals. Alongside potential negative impacts to human systems, stormwater can carry biological contaminants into estuaries, forcing the closure of shellfish beds and beaches. In communities with combined sewer systems, excessive stormwater can cause the release of raw sewage into waterways. The timetables associated with different impacts run the gamut from those occurring immediately to many years after a flood event.

Climate change and variability are predicted to impact nearly every aspect of the hydrologic cycle, complicating the efforts of governments and nongovernmental entities to manage stormwater and its impacts (Funkhouser 2007; Hirschman et al. 2011; Zhou et al. 2012). For example, alterations in the seasonality, duration, form, and amount of precipitation can lead to different stormwater flows. For many North American communities, climate change and variability will likely mean an increased likelihood of flooding, although there will be regional variation (Hirschman et al. 2011; Melillo et al. 2014). Furthermore, climate change models predict that the timing and seasonality of precipitation may change, both of which could affect patterns of runoff (Hirschman et al. 2011; Melillo et al. 2014). In most regions, but especially the U.S. Northeast, Southeast, and Midwest, precipitation is predicted to fall in more intense events. Climate models predict the overall quantity of precipitation in North America to increase while also shifting to higher latitudes. Precipitation effects will be exacerbated in coastal areas by sea level rise (Hirschman et al. 2011; Rosenzweig et al. 2011; Melillo et al. 2014). Sea levels are projected to rise from 1 to 4 ft during the coming century in most North American coastal cities. Higher seas increase flooding by making it more difficult for standing water to drain. Coastal communities are particularly vulnerable to stormwater damage because flooding linked to intense precipitation or drought inland can combine with sea level rise and ocean storms to hit them particularly hard.

Policy responses to address climate change and sustainability more generally also impact stormwater and its management. For example, because the lifespan of most stormwater infrastructure is 50–100 yr, infrastructure being installed today needs to be designed for the climate of tomorrow (Arisz and Burrell 2006; Ashley et al. 2005; Mailhot and Duchesne 2010). However, present stormwater management designs are largely based on historical precipitation patterns, as described in the federal government's Technical Paper 40 (Hershfield 1961). Only recently did the Environmental Protection Agency (EPA) upgrade its stormwater management tool for new precipitation patterns expected to result from climate change (EPA 2015). In addition, efforts to integrate sustainability and mitigation of greenhouse gas emissions into urban development are driving planning that emphasizes more dense and low-impact development (Hamin and Gurran 2009; Pyke et al. 2011). When development patterns result in less open space, a tension results with stormwater management strategies that rely on environmental features of the landscape to channel and store stormwater.

For all these reasons, there is today a much greater need for coordination among different agencies and private entities at the local, county, state, and federal levels; consideration of locally specific factors that shape stormwater and its management opportunities; and incorporation of the dynamic nature of evolving precipitation patterns into planning (Rosenberg et al. 2010; Hanak and Lund 2012). The informational base that has historically informed stormwater management is becoming less reliable as the climate regime changes. At the same time, climate models are also uncertain and have limited value to decision-makers at local scales.

In this context, local stormwater managers have begun turning to decision support tools that integrate climate science for scenario-based planning and that help decision-makers make trade-offs on performance objectives [Semadeni-Davies et al. 2008; Kirshen et al. 2015; WERF 2010; Cheng et al. 2009; Jia et al. 2013]. Scenarios describe possible future states that can emerge from expected conditions with assumptions about driving forces and system changes (Berkhout et al. 2002). They are "lenses" that focus well on some aspects of a system but can fail to illuminate others. For example, hydrodynamic models can provide information about flood frequency and depths under different conditions (Miller et al. 2014), geographic information systems (GIS) can highlight critical facilities or areas likely to be flooded with assumptions about future greenhouse gas emissions and development patterns (Moore et al. 2012; Sample et al. 2001; Shamsi 2005; Viavattene et al. 2008), and optimization models can assess performance of a plan or infrastructure under many different conditions (Kirshen et al. 2015). The U.S. EPA has developed a scenario-based tool [the Storm Water Management Model (SWMM)] that can help stormwater managers understand how existing infrastructure will perform under possible future conditions (EPA 2015). SWMM models hydrological systems to estimate the impacts on water quantity and quality of different engineered stormwater solutions. Tools such as these provide detailed information about the specific aspects of broader systems producing stormwater and managing stormwater.

While decision support tools can enable deeper understandings of specific elements of system behavior, they also have their limits [for a comparative summary of 20 commonly used tools, see Jayasooriya and Ng (2014)].[1] Jayasooriya and Ng's review focused on five criteria: number of practices the tool can support, the modeling approach, data needs, accuracy, and regional limitations. To this we would add that decision support tools that use a scenario-based approach can also serve a more general, diagnostic purpose by helping local decision-makers identify—and learn about—the linkages among climate stressors, impacts, and adaptation strategies with close attention to how they may be manifested in specific social, institutional, economic, and environmental contexts. In their review, Jayasooriya and Ng point to stakeholder involvement in stormwater management as one of the key research challenges. In particular, they identify a need to obtain participant interaction in the selection of scenarios. In this paper, we discuss our experience with a structured dialogue process to do just that. The process is designed to help decision-makers develop scenarios that identify a range of consequences from stormwater and efforts to manage stormwater. By design, the Vulnerability, Consequences, and Adaptation Planning Scenarios (VCAPS) process helps to elucidate and diagnose local complexities and couplings and encourage learning (Kettle et al. 2014; Webler et al. 2014; Tuler et al. 2016). None of the 20 models that Jayasooriya and Ng reviewed does what the VCAPS tool does. Instead VCAPS is an answer to the call for research that Jayasooriya and Ng make. Here, we draw on applications of the VCAPS process to coastal communities to illustrate how the process helps managers confront pressing stormwater challenges. VCAPS provides an important addition to existing tools because it engages local stakeholders in the generation of scenarios, and it empowers managers to assess the future implications of runoff on multiple dimensions in a particular context. A diagnostic process like VCAPS can help managers decide where to direct additional studies and assessments, make distinctions between tolerable and intolerable risks, and build public support for action.

2. A tool to help stormwater managers plan

The VCAPS process is a dialogue-based diagramming process that helps communities assess vulnerability to natural hazards. Decision-makers, technical experts, and residents come together to document the state of local and expert knowledge about the origins and consequences of stormwater in a specific municipality. Participants explore how the contextual factors of coupled human and natural systems influence the causes, dynamics, and impacts of stormwater and the effectiveness of potential management actions. Contextual factors include behavioral, social, cultural, economic, institutional, and environmental features of the local community that may impact vulnerability and risk. The process supports local vulnerability assessment and climate adaptation planning (Kettle et al. 2014; Webler et al. 2014).

Since 2008 we have implemented VCAPS in 14 communities in seven states (Kettle et al. 2014; Webler et al. 2014).[2] Of all the VCAPS processes, 10 explicitly considered stormwater management in the context of various climate and weather stressors, including heavy precipitation events, severe storms coupled with storm surge, and sea level rise (see Table 1).

Our development of VCAPS draws on the intellectual history of hazard management (Clark et al. 1998; Kates et al. 1985), climate vulnerability assessment (Dow and Carbone 2007; Kasperson et al. 2005; Smit and Wandel 2006), and analytic deliberation (Stern and Fineberg 1996; Dietz and Stern 2008; Webler and Tuler 2008). It shares features with other approaches that explore cause–effect pathways linking climate stressors, hydrologic processes, and implications for stormwater and wastewater systems (WERF 2010).

Figure 1 summarizes the three basic phases in VCAPS: preparing, scenario building, and reporting. [See Webler et al. (2014) for more details.] The work usually begins with an invitation by local officials who want to sponsor a VCAPS process. In the preparing phase we identify and recruit participants and collect background information relevant to understanding past planning, hazard events, and ongoing concerns within the community. In interviews with key stakeholders and officials, we learn about the history of the problem and the reason for the community's interest in examining their stormwater problems in greater detail. We also discuss with the local officials sponsoring the process how best to implement the process. This includes defining the number of meetings, their timing, and the participants. We work collaboratively with the local sponsor to design the process in a way that is responsive to the community's need and preferences. This helps to promote legitimacy, build

[1] The European Commission's SWITCH (Sustainable Water Management Improves Tomorrow's Cities' Health) research partnership maintains a website with a menu of decision support tools for water management and an extensive list of publications (http://www.switchurbanwater.eu/index.php).

[2] For additional information about VCAPS and communities in which it has been applied, including summary reports, see www.vcapsforplanning.org.

TABLE 1. Implementations of VCAPS.

Location	Climate stressors discussed	Format of meeting(s)	Participants
Beaufort, South Carolina	Sea level rise and extreme rainfall impacts on flooding	Two all-day meetings in 1 month	12
Beaufort, South Carolina	Drought and extreme rainfall impacts on blue crab fishery	Two half-day meetings (separated by 2 months)	5
Boston, Massachusetts	Winter storms; flooding from precipitation and storm surges; extreme heat	Five 2-h meetings	Approximately 90
Dauphin Island, Alabama	Severe coastal storms in combination with sea level rise	One full day	15
McClellanville, South Carolina	Heavy precipitation; sea level rise	Two half-day meetings (over two consecutive days)	6
New Bedford and Fairhaven, Massachusetts	Extreme coastal storms	Two half-day meetings (separated by one week)	13
Orange Beach, Alabama	Heavy rainfall; severe coastal storms	One full day	13
Plymouth, Massachusetts	Flooding (as result of sea level rise and increased precipitation); coastal erosion (stronger and more frequent storm events)	Two half-day meetings (separated by one week)	6
Plymouth, North Carolina	River level rise (as a result of heavy precipitation upland, tropical storms, sea level rise, and local major rainfall events)	Two 2.5-h meetings (over two consecutive days)	7
South Thomaston, Maine	Precipitation; sea level rise; ocean temperature	Two all-day meetings in 1 yr	12
Sullivan's Island, South Carolina	Extreme rainfall; sea level rise; higher high tides	Four 2-h meetings (over 2 months)	9

trust, strengthen motivation to participate, and enhance accessibility.

The second phase—scenario building—involves participants discussing, exploring, and learning about climate change–related risks, vulnerabilities, and adaptation strategies. In this phase the group defines scenarios and diagrams pathways through which precipitation produces stormwater and stormwater impacts the community. We usually start the first meeting with a presentation by a local climate expert to summarize regional climate trends, projections, and potential impacts to the community. The purpose is to help participants visualize how climate variability and change may change stormwater flows. We then facilitate a discussion among all participants and invited experts to clarify how the community may be impacted. Integrating and sharing information about local interactions between biophysical and social contexts is important in understanding local phenomena, balancing competing priorities and values, policy making, and managing coupled human–environment systems (Picketts et al. 2012; Berkes and Folke 2002). We can also begin with

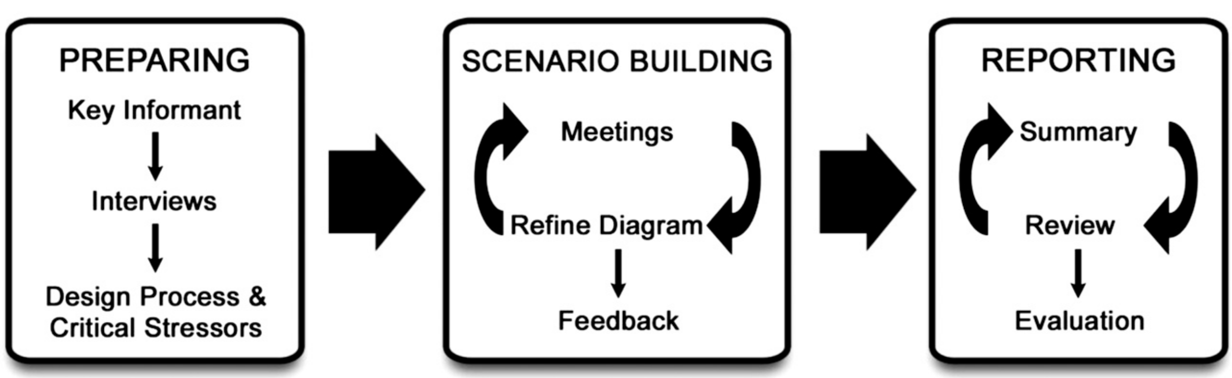

FIG. 1. Schematic of the three phases of a VCAPS process.

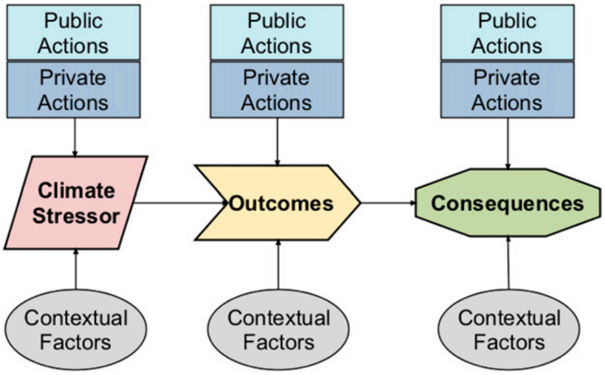

FIG. 2. Building blocks of VCAPS diagrams.

discussions of what kinds of mitigation and adaptation actions have been implemented previously or how the VCAPS process intersects with other planning activities (e.g., hazard mitigation planning).

The main focus of the second phase is to introduce VCAPS and explain how the diagramming works. One of the important characteristics of VCAPS is that very detailed diagrams are built using only six components. The basic structure of a VCAPS diagram is shown in Fig. 2. Diagrams usually start by defining a *management concern*, which frames the issue the participants are examining in a decision-making context. Examples include stormwater management, coastal erosion, public health, or emergency management. These are represented by trapezoids in the diagram.

The second element is the *stressor*. Stressors are external forces that create change in the system. In the context of stormwater management, stressors produce or modify stormwater flows. Examples include sea level rise, intense storms, temperature extremes, and drought. The choice of the stressors for the scenarios is made by the participants. Stressors can be defined generally or with great detail (e.g., a winter storm with 24 in. of snowfall).

The third element is the *intermediary outcome*. These help characterize the present state of the coupled human–environment system. Outcomes are represented by block arrows. This element includes a diverse set of features and is used to describe the state of any aspect of the system being studied. For example, the group may characterize the degree of flooding in roadways, the penetration of stormwater into buildings, or the behavior of people, among any number of other aspects.

The fourth element in the VCAPS diagram is the *consequence*, and this is represented as an octagon. Consequences are a special set of system states. We distinguish consequences as system states for which it makes sense to ask the following question: ''Why do we care about this?'' These are end states people care about. For example, stormwater penetration into a building is an intermediary outcome, not a consequence, because it is not unreasonable to ask why we care about it. Consequences specified by participants in past VCAPS processes about stormwater infiltration to buildings have included health effects from mold, costs associated with property damage, loss of tax revenue, and the trauma associated with losing personal items. A longer list is given in Table 2.

The fifth element is the *contextual factor*, represented by ellipses. These are characteristics of the local system that shape the way the stressor impacts the system. For example, stormwater impacts depend on the community's physical location, features of the natural and built environments, infrastructure, regulatory systems, demographics, and so on. A longer list is provided in Table 3. During the process we elicit information about behavioral, social, cultural, economic, institutional, and both built and natural environmental factors that increase or decrease three dimensions often associated with vulnerability: exposure, sensitivity, and the capacity to act (Adger 2006; Kasperson et al. 2005).

We also encourage participants to think about how contextual features may change and how climate change and variability can be one driver of change. For example, types of vegetation and disease vectors may shift with changing temperatures and rainfalls, which can alter the uptake of moisture from soils and shift drainage patterns; the permeability of soils may change during prolonged droughts; and sea level rise may impact groundwater tables and reduce marsh habitats that can act as filters of stormwater.

The sixth element in a VCAPS diagram is the *management action*, represented at the top of the diagram as rectangles. We usually distinguish public from private actions. There are many public and private strategies and best management practices to address stormwater.[3] Management actions can be implemented ''upstream'' (i.e., closer to the climate stressor) or ''downstream'' (i.e., closer to the consequences). Upstream actions include large-scale stormwater conveyance infrastructure improvements and impervious surface regulations intended to help prevent problems from arising. Causal pathways linking stressors and consequences may be blocked by multiple management actions. For instance infrastructure improvements may require public education, financing, or policy changes. Discussions about

[3] For example, the EPA maintains a menu of best management practices and case studies at https://www.epa.gov/npdes/national-menu-best-management-practices-bmps-stormwater#edu.

TABLE 2. Examples of potential impacts from stormwater runoff and flooding identified in VCAPS processes.

Public health impacts
Contamination of drinking water
Contamination of shellfish and beaches
Impassable roads and access to emergency services from flooding
Manhole covers ejected
Standing water hosts disease vectors
Damage to utilities that disrupt home medical services and egress from buildings
Economic impacts
Cost to municipality for response, repairs, and maintenance
Loss of revenues from shellfish sales
Loss of recreational permit fees
Loss of business revenue
Increase in property insurance costs
Costs for dredging of waterways to remove debris and sediments
Institutional impacts
Changes to local land-use ordinances and building codes
Built environment impacts
Damage to culverts, roads, and utilities
Overtaxing of wastewater treatment facilities
Property loss or damage
Social impacts
Loss of beach use
Controversy about changes to land-use ordinances
Natural environment impacts
Habitat destruction
Riverine bank destruction
Erosion and landslides
Chemical contamination of waterways

TABLE 3. Examples of contextual factors that influence stormwater management identified in VCAPS processes.

- Local topography
- Area of vegetated land
- Amount of impervious surface from development and land-use changes
- Capacities of sewer systems, drainage ditches, catch basins, ponds, and lakes
- Local ordinances and their enforcement
- Willingness of residents to voluntarily clear drainage ditches
- Coordination among government agencies at different levels
- Soil saturation levels and groundwater table levels
- Local budgets
- Local demographics
- Preferences for development patterns

management actions informed by understanding of local contextual factors can highlight trade-offs. Improved maintenance of culverts, drainage ditches, and stream beds can mitigate the severity of impacts, but also can be difficult to implement if access is not available because of past development patterns. Public education about landscaping that reduces runoff and the need to improve infrastructure to accommodate climate change has proven useful in some cases but may not have a large impact on overall volumes and flows. Downstream improvements in emergency management and insurance can reduce impacts and support more rapid recovery, but they do not necessarily prevent adverse impacts from happening. In some cases, management actions can lead to a new series of outcomes and consequences.

Facilitating discussions and mapping or diagramming the conversation using the six components occurs in real time using a laptop and a projector. We use freeware called Visual Understanding Environment (VUE; available for free at http://vue.tufts.edu/), but other software can work just as well. As causal chains become developed, the facilitator encourages participants to identify management actions that could be taken by public and private entities. We ask participants to think about "no regret" strategies, which offer immediate benefits whether or not projected storm and flooding events occur, and "low regret" strategies, which present greater resilience at limited cost. We encourage participants to consider strategies of protection, accommodation, and retreat that can be implemented in different time scales (Kirshen et al. 2008, 2015; Douglas et al. 2013; Waters et al. 2003). We also encourage participants to discuss trade-offs, local contextual features, and availability of resources that can facilitate or hinder implementation of management actions. The facilitated discussion promotes systems-based thinking by having participants consider linkages among elements of coupled human–environment systems. VCAPS also promotes learning when participants share different information and experiences in discussions that allow considerable opportunities for questions and answers in a collegial setting (Tuler et al. 2016). It also identifies critical gaps in the knowledge base.

Finished VCAPS diagrams can be quite complex and large. Figure 3 illustrates a simplified example of pathways associated with runoff in one community. In this case, heavy rainfall leads to runoff, which erodes road beds. When road beds erode, transportation is inhibited, which can reduce emergency services, require detouring of school buses, and result in longer commute times. Utilities can also be disrupted. Consequences include increased costs to the city for repairs. In Fig. 3, a second pathway related to heavy flows in drainage ditches suggests that drainage infrastructure can become blocked with debris transported by the water. Blocked drainage ditches can result in standing water, flooding of roads, and flooding of properties, leading to additional repair expenses. Public safety may be compromised by blocked roadways. To prevent or mitigate this variety of outcomes and consequences, management actions can be implemented. Some are shown in Fig. 3.

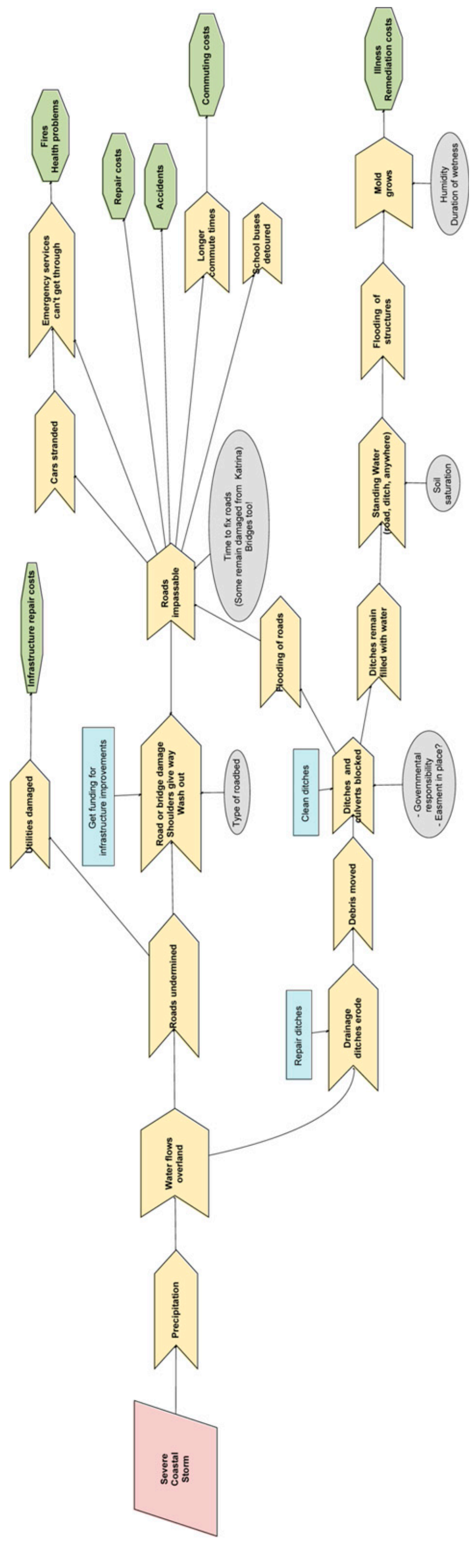

FIG. 3. Simplified VCAPS diagram.

The third and final phase of the VCAPS process is the reporting phase. Here, the team summarizes, reviews, and evaluates results from the meetings. Working with the local sponsors of the process, we present information in ways that facilitate its integration into local planning, which may be associated with hazard mitigation planning, comprehensive planning, or adaptation planning (e.g., City of Boston 2013). The Federal Emergency Management Agency (FEMA) is now requiring more formal consideration of climate change in development of hazard mitigation plans (FEMA 2015). Depending on participant preferences, the process may conclude with discussions about how to prioritize and schedule implementation of management actions. We use participant checking to validate results.

3. Meeting challenges to stormwater management with VCAPS

In a context of increasing change and variability in climate, stormwater managers are facing new challenges in already complicated systems. Participants in the 10 communities where we implemented VCAPS highlighted a set of particularly pressing challenges. In this section, using the examples from the communities listed in Table 1, we illustrate these challenges and how VCAPS has helped participants address them. VCAPS, as an example of scenario-based qualitative decision support tools, helped stormwater managers identify and diagnose challenges, decide where to direct additional studies and assessments, make distinctions between tolerable and intolerable risks, and build public support for action.

a. *Challenge: Characterizing the implications of interacting climate stressors that originate stormwater*

In our experience, managers are often reluctant to suggest scenarios that have not happened in the past and to discuss what are thought to be remote possibilities. Regional climate models are improving but do not provide predictions at the scale sought by local decision-makers. VCAPS helps local managers overcome resistance to developing qualitative scenarios using existing local knowledge. Diagramming of qualitative scenarios is relatively quick, as facilitators use a line of questioning that taps local knowledge and promotes creative thinking. We intentionally design the setting to encourage people to be inventive about what just might happen. VCAPS enables participants to explore qualitatively how interacting climate stressors can impact the dynamics of stormwater and the effectiveness of stormwater management strategies. Through creating diagrams, managers learn how multiple stressors can work in concert to exacerbate stormwater flows and impacts.

For example, participants in McClellanville, South Carolina, noted that increased rainfall variability and heat may alter the structure of soils, leading to much lower rates of infiltration than would be expected if rain came in smaller amounts more regularly. The consequence is much higher rates of runoff. Pollutants such as organic wastes can build up in soils and drainage systems during dry periods. Downpours wash them into the water in a strong pulse where they impact local water quality in streams and surface waters that are valued for ecological or recreational reasons.

In Beaufort, South Carolina, participants identified how a combination of heavy rainfall events and sea level rise can interact, such that the existing stormwater infrastructure becomes overloaded. In many parts of the community, elevation is low and conveyance of stormwater to the sea is slow. Sea level rise will exacerbate the problem. In a VCAPS process in New Bedford and Fairhaven, Massachusetts, participants noted that the harbor hurricane barrier is often closed in advance of an approaching hurricane. This protects the inner harbor and downtown areas from storm surge. However, if a storm deposits large amounts of precipitation on land and the storm lasts long enough, the water levels in the inner harbor can rise. At some point, the outfall pipes along the Fairhaven shoreline become submerged, which inhibits the conveyance of stormwaters from the town center, leading to property damage, closure of shellfish beds, damage to a public park, and contamination of drinking water wells.

b. *Challenge: Bringing all available expertise and local knowledge to bear on a problem*

Stormwater managers are confronted with myriad factors that influence flows of runoff and the impacts of runoff. Participants in the Boston VCAPS discussion elaborated how diversion of runoff into parks can impact recreational opportunities for at-risk youth. Historical preservation staff pointed to the need to maintain groundwater at high levels so that wooden pilings do not rot. Advocates for the homeless discussed how stormwater flooding impacted that vulnerable population. Public health officials identified the challenges to health care when providers and social service agencies cannot maintain visits to those receiving health care at home because of flooded streets. Emergency managers discussed related issues associated with keeping emergency shelters safe. Residents who are evacuated naturally wish to bring their pets, but there was at that time no safe way to keep them in shelters. In addition, people may not have their medications and addicts may not receive treatment (e.g., methadone) in shelters, which increases safety challenges. The task of identifying such issues was facilitated by having participants representing diverse communities, agencies, and organizations talk with each other and collaboratively develop elaborate scenarios for which they would like to plan.

Bringing a wide range of expertise and knowledge to bear on the problem of stormwater also facilitates learning, which can build capacity and lead to more effective planning. VCAPS is designed to enhance capacities for thinking and to advance planning rather than achieve a specific outcome. This is one reason why stakeholders agree to participate. While we have implemented VCAPS with communities that are interested in planning for climate change and variability, a more general intention has been to support planning and learning in participatory modeling (Tuler et al. 2016). Learning is supported by having people with varying perspectives and knowledge talk and reflect. However, it takes more than just having people in the same room together to promote learning. The structured discussions and diagramming to develop scenarios are key to facilitated learning. Three quotes from participants illustrate how the process of involving diverse participants in structured discussions enhances learning:

- "What I learned were new perspectives, different stories about how they are impacted, the community, and parts of the community."
- "What I really like about them [the VCAPS diagrams] is that they are visual and they level the playing field for everyone at the table. People bring in very different backgrounds, very different sets of experiences, all trying to communicate around what can be a very complex area, so it being very visual and going from one step to another, very cause–effect oriented, it levels the playing field for everyone there. That is its biggest value."
- "I think the VCAPS process was an opportunity for everybody to see the same information displayed at the same time and have an opportunity to synergize our knowledge base."

c. *Challenge: Integrating local and scientific information about coupled human–environment systems*

While stormwater managers and local decision-makers often have considerable detailed experience with their community, they may also lack access to information about hydrological dynamics and management strategies. Scientific experts, on the other hand, may not be aware of how specific social, political, economic, and environmental features of a local community can impact the character of stormwater dynamics or the effectiveness of management strategies. A challenge is to bring these two types of knowledge together to inform planning, especially as patterns evolve because of climate change.

By creating a space for creative thinking, VCAPS enables participants to explore how multiple systems can be interconnected with stormwater management. For example, flooding can disable wastewater management facilities; interfere with the delivery of emergency services, home medical services, public transportation, and school busing; disrupt access to recreational facilities; or promote public health risks from bacteria, insects, or mold. Complex and tight coupling among natural and human systems makes stormwater management critically important and increasingly complicated.

Diagramming scenarios provides a structure to elicit information about local and expert knowledge of coupled systems and cascades of impacts. For example, in Fairhaven, Massachusetts, participants discussed how homeowners' sump pumps transfer toxic contaminants from basements to the harbor, necessitating closure of commercial and recreational shellfish beds. These closures have subsequent impacts to municipal finances because licenses are not sold and cleanup costs are elevated. Participants also noted how floodwaters mobilize unsecured propane tanks from homes, creating ''floating bombs''—another threat to public health and safety.

Because of the tight and complex coupling between systems, many of the consequences are difficult to foresee, but through group discussion informed by nuanced, local knowledge and real-time diagramming, potential pathways can be elaborated. For example, flooding in Plymouth, North Carolina, led to outflows from the swamps days later that were high in nutrients. This led to low dissolved oxygen (hypoxia) that resulted in a massive fish kill along the Roanoke River. Participants noted that the speed with which dams upriver released water also affected nutrient levels in the river. In addition to flies and public health threats resulting from the dead fish, the town faced the cancellation of several of its fishing tournaments for up to 3 years. Lost revenue from tournaments was expected to have severe economic consequences for Plymouth's tourism business.

d. *Challenge: Identifying management actions and their trade-offs*

There are many possible strategies for managing stormwater runoff and its consequences. The relevance of strategies in specific contexts is affected by local economic, political, social, and institutional factors and may require consideration of multiple trade-offs between, for example, cost, effectiveness, and public acceptance. The implementation of stormwater management actions can also result in new undesirable consequences in a community. Thus, stormwater managers and local decision-makers can be faced with difficult decisions about trade-offs. VCAPS allows participants to identify and explore the implications of upstream and downstream actions that can be implemented by both public agencies and private entities, such as businesses, local developers, and homeowners.

For example, VCAPS discussions about stormwater and its impacts in Boston revealed multiple opportunities for management upstream and downstream, including the following:

- elevating utilities and installing emergency generators;
- reducing runoff by strategic plantings of vegetation to take up water, building of rainwater gardens, and decreasing of impervious surface areas;
- managing runoff by keeping street drainage clear, building additional culverts, and raising curbs and directing ponding into low-lying areas;
- increasing capacity of conveyance infrastructure by increasing pipe diameters and repairing pipes to reduce infiltration rates; and
- addressing flood impacts by pumping out streets and buildings, cleaning up dispersed pollutants, and purchasing insurance.

Stormwater managers can emphasize public or private actions, but preferences may be related to broader contexts of community growth and preferences. For example, shifting development patterns may lead to greater emphasis on stormwater infrastructure being privately owned and maintained, including retention ponds in housing developments. Local ordinances may also evolve in response to climate change and variability. An action proposed to manage stormwater in Beaufort, South Carolina, would require developers to establish an escrow fund with an allocation for each lot so the neighborhood would have the funds to directly pay for the maintenance of local roads and stormwater ponds.

Stormwater management actions can have unintended impacts, and they can be difficult to anticipate in a time of increasing climate change and variability. For example, in McClellanville, South Carolina, participants noted that standing water from clogged and inadequate stormwater drainage systems provides habitat for mosquitoes, but management actions taken in the past have raised concerns about environmental health risks. Management strategies that can be used to reduce mosquito populations include public education, spraying that kills either mosquito larvae or adults, and adding mosquito eating fish to water sources. There are concerns that increased spraying over the long term to address a growing mosquito problem might lead to health effects in the community, loss of insect populations (e.g., butterflies and fireflies), impacts to commercially important shrimp and crab populations, and increased costs of abatement programs to cash-strapped counties.

In Sullivan's Island, South Carolina, the VCAPS process revealed that regulations requiring lot elevations can have unintended impacts to adjacent property owners. If a primary homeowner elevates a lot, then waters may be pushed onto neighbors' properties. If regulations are created to keep all stormwater on a lot (e.g., with swales), then groundwater levels may increase, which can cause more infiltration into the already overtaxed wastewater system. Because of the uncertainties and complexities associated with climate change and variability, newly emerging connections between systems and impacts from management actions may not be easily anticipated without an opportunity for discussions that focus on contextual details features of the system and promote creative thinking.

e. *Challenge: Coordinating actions among multiple public and private entities*

Climate change and variability may introduce new linkages or change existing linkages that will require new forms of coordination for successful stormwater management. As shifting climate and weather patterns take hold, existing gaps, conflicts, and overlaps in management may also be revealed. For example, participants in Plymouth, North Carolina, and McClellanville, South Carolina, discussed the need for coordination with upstream authorities. Local officials in Plymouth identified the need for coordination with relevant authorities upriver in Virginia to ensure controlled dam releases and with other North Carolina state agencies to restock the river with fish. Participants in the McClellanville VCAPS process identified the challenge of coordinating with the county, noting that the town can mitigate flooding caused by clogged drainage ditches by ensuring that easements are established both within and outside the municipal limits. Charleston County will clear drainage ditches on private property if easements are in place, but unfortunately they are not always in place for all properties on a street. When that is the case, the county sometimes skips maintenance for the entire street. Three barriers that discourage some private landowners from setting up easements are fears that they may reduce property values, reduce use of the area, and increase costs to the property owner because of surveying requirements. There is also a concern that establishing easements on public land may restrict the use of those lands. Participants in the VCAPS process suggested that the town facilitate easements by reducing the costs to property owners, updating town ordinances, and providing for public easements where appropriate and that these needs are more pressing with predictions for more heavy rainfall events and as a result of climate change.

In Boston, VCAPS participants noted that the stormwater management system was well understood by leadership in the water and sewer authority, but this knowledge was not systematically recorded or available to people in other departments. Given the complexity of the system, it was difficult for even the most experienced people to predict how the system would respond to a combination of weather or climate hazards.

4. Conclusions

Historically, stormwater managers confronted comparatively stable hydraulic regimes and regulatory compliance was limited to large municipal systems. But over the past 15 years we have seen increasing variability in temperature and precipitation, while at the same time EPA expanded compliance to many more stormwater systems. A 2010 lawsuit with the Chesapeake Bay Foundation means even stricter stormwater management rules are in the offing.[4] Moreover, coupled human–nature systems continue to be in constant transition in most localities with new development, site redevelopment, habitat reconstruction, wetlands banking, and other related hydrologic challenges such as dam removal and creek daylighting. In a nutshell, the job of stormwater management is becoming increasingly important and increasingly difficult.

To confront this new reality, stormwater managers need new decision support tools that will help them characterize the threats, build collaboration among institutions and stakeholders who can contribute to managing stormwater, and generate management solutions. EPA's revision to their stormwater management model (EPA 2015) helps with the engineering solutions, but there remains a need for tools that generate planning scenarios for stormwater challenges while also promoting learning and coordination across stakeholders, agencies, and sectors. To explore the ramifications of future threats, stormwater managers will need to better

[4] See http://yosemite.epa.gov/opa/admpress.nsf/0/ac46af32562521d48525772000591133?OpenDocument.

understand the climate-sensitive drivers of stormwater, the linkages among human and natural systems that change runoff, and synergies and tensions that can arise in planning for a diverse range of potential scenarios.

The VCAPS process illustrates the benefits of a qualitative and participatory scenario-based decision support tool for stormwater management. It is a structured process of dialogue and learning that involves stakeholders in a mapping exercise oriented toward describing, prioritizing, and resolving local stormwater challenges. The process integrates information derived from various sources and uses multiple tools—such as GIS, performance assessments of infrastructure, and systems dynamics and optimization modeling from multiple stakeholders—to arrive at thorough characterizations of local threats and opportunities for management. One key benefit of VCAPS is that it offers a way to integrate local knowledge and experiences with technical expertise.

As with all planning processes, the results of a VCAPS process depend on the participants involved because the process is steered and informed by its participants. VCAPS organizers and participants can use outside experts to validate information in the diagrams. If participants realize that relevant knowledge is missing, we have seen them recruit additional people to fill gaps. We have elected to use this approach because of our focus on helping stormwater managers diagnose potential problems that may emerge from climate change and variability. The information generated as part of VCAPS can subsequently be used to determine additional worthwhile studies and assessments that will be subject to further scrutiny, which can also reveal gaps that participants did not identify. Additionally, subsequent efforts that utilize information based on VCAPS diagrams can be validated by public review, such as public hearings that may be required as part of a planning process.

Our experiences with conducting the VCAPS process in 10 communities along the U.S. Atlantic and Gulf coasts revealed it to be a promising tool to plan, implement, and assess stormwater management actions. The process is flexible enough to work in small towns or large cities. It can accommodate variance among communities and regions because it allows the development of scenarios based on local knowledge and regional-specific information. It can be conducted in a few weeks or over many months, depending on the level of detail and depth that is desired. It produces characterizations of the problem and systems that are localized. It produces solutions that are also highly specific to local place. Perhaps one of the most valuable aspects of the process is that it produces transparent justifications for recommended management or policy actions. Nuanced understandings of subjective and qualitative dimensions of decisions are important factors in consideration of not only what strategies might work but also which are likely to be acceptable. While VCAPS is by no means the only decision support tool, it addresses key challenge of stormwater management to obtain participant interaction in the selection of scenarios (Jayasooriya and Ng 2014). As we continue to wrestle with the changing problem of stormwater management, research into new tools is a continuing need.

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